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IT'S NOT A BIG SKY AFTER ALL: JUSTIFICATION FOR A CLOSE APPROACH PREDICTION AND RISK ASSESSMENT PROCESS

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There is often skepticism about the need for Conjunction Assessment from mission operators that invest in the "big sky theory", which states that the likelihood of a collision is so small that it can be neglected. On 10 February 2009, the collision between Iridium 33 and Cosmos 2251 provided an indication that this theory is invalid and that a CA process should be considered for all missions. This paper presents statistics of the effect of the Iridium/Cosmos collision on NASA's Earth Science Constellation as well as results of analyses which characterize the debris environment for NASA's robotic missions.

INTRODUCTION

NASA has performed routine Conjunction Assessment (CA) for its manned space program since the STS-26 mission (the seventh flight of Space Shuttle *Discovery*) in 1988. On the other hand, no official requirement for unmanned, or robotic, missions existed until the NASA Procedural Requirements (NPR) for Limiting Orbital Debris[1] was updated in August of 2007 to include CA requirements. The policy requires routine conjunction assessment processing for all maneuverable robotic missions that have perigees less than 2000 km or that orbit within 200 km of the geosynchronous ring. The NASA Robotic Conjunction Assessment (CA) Team at Goddard Space Flight Center (GSFC) was charged with providing the conjunction assessment/risk analysis (CARA) services for the predicted close approaches for NASA's unmanned missions. However, owner/operator management was often not receptive to initiating the service for their missions because of lack of funding combined with a perception that space is big, and that the probability of having a detrimental collision was essentially non-existent. Most operators had many years of space operations experience and thought that if they hadn't had any issues in the past, they weren't likely to have problems in the future. This perception that the likelihood of a collision is so small that it can be neglected is commonly called the "*big sky theory*".

However, relying on the past to predict the future is not a reliable data point. The threat to operational spacecraft health and safety from orbital debris has been on the increase over the past several years. Because of this constantly increasing amount of orbital debris, the possibility of losing an active satellite due to a collision has grown substantially. The NASA Robotic CA Team developed several methods to quantify the increased risk to help justify the existence and associated cost of the CA process. However, the best justification came on February 10, 2009. On that date, a collision between the active Iridium 33 satellite and inactive Russian payload Cosmos 2251 altered the perception of skeptics by proving that the big sky theory is no longer valid and that a formal CA process should be an operational consideration for all missions flying in debris-rich regimes.

This paper describes the methods used by the NASA Robotic CA Team to predict and quantify debris risk for spacecraft in various regimes. In addition, the paper presents statistics of the effect of the Iridium/Cosmos collision on NASA's Earth Science Constellation, residing in a slightly lower 705 km altitude orbit.

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BACKGROUND

In January 2005 the National Aeronautics and Space Administration (NASA) GSFC began receiving routine conjunction assessment screening data from the United States Strategic Command (USSTRATCOM) for the Earth Science Constellation (ESC) missions, which consist of 11 satellites in 705 km mean altitude sun-synchronous orbits, and the Tracking and Data Relay Satellite (TDRS) constellation of nine geosynchronous communications satellites. These screenings compare the predicted trajectory of each spacecraft with the trajectories of objects in the High Accuracy Space Object Catalog. This screening data is used to evaluate the risk posed by each predicted close approach event and provide recommendations to Owner/Operators regarding potential mitigation options. (Conjunction Assessment is often confused with Collision Avoidance, which is the act of performing a maneuver to mitigate the threat posed by a conjunction.)

On January 11, 2007, the Chinese performed a test of an Anti-Satellite weapon, destroying one of their inactive weather satellites, FengYun 1C. This event created over 2000 pieces of debris in an 861 km sun-synchronous orbit. The Earth Science Constellation missions began having conjunctions with FengYun 1C debris within weeks of the event, so it was very fortunate that the CA process was in place to address the threat. FengYun debris made up 10% of the conjunctions for the Constellation, and has since grown to make up about 15%. Detecting these close approaches depends on the debris objects being "catalogued" (by the Joint Space Operations Center at Vandenberg Air Force Base) following the breakup event. This process is labor intensive, and can take weeks or months for a debris cloud of such magnitude. The NASA Robotic Conjunction Assessment process can only be used to protect NASA missions once the objects are in the catalog.

In August 2007, NASA formalized its commitment to mitigating potential on-orbit collision risks by adding CA requirements to the NPR. Because the updated NPR requires that conjunction analysis be performed routinely for all Earth-orbiting spacecraft, the mission set supported by the NASA Robotic CA team began to grow. By the time of the Iridium/Cosmos collision in February of 2009, the suite of missions receiving service had grown to encompass 27 maneuverable missions from across NASA in several different orbit regimes. Following the collision, which generated over 1000 pieces of debris, NASA management decided to make the CARA process for the Agency more robust by requiring routine support for non-maneuverable missions and non-operational NASA assets. In this way, nearby operators of maneuverable assets could be made aware of impending close approaches with NASA objects that NASA had detected but couldn't mitigate. The Robotic CA process therefore grew rapidly once again, adding 22 non-maneuverable missions by mid-May, with plans to add 21 non-operational objects starting October 1, 2009 when the screening data becomes available from USSTRATCOM.

NASA ROBOTIC CA PROCESS OVERVIEW

The NASA Robotic Collision Assessment/Risk Analysis team performs collision risk assessment analysis based on the data provided by Orbital Safety Analysts (OSA) resident in the Department of Defense's Joint Space Operations Center (JSpOC). The process begins by generating close approach predictions between assets and other objects in the United States Strategic Command's (USSTRATCOM's) high-accuracy catalog. Three different mission safety volumes are used in the screening process as defined in Table 1 for LEO and geosynchronous (GEO) regimes. The safety volumes are centered on the primary object and dictate different data product deliveries as well as actions taken by the CA Team. The "Monitor Volume" is the largest safety volume and serves as the initial reporting filter. The "Tasking Volume" is a smaller volume, and close approach predictions that fall within this volume require further analysis. The "Watch Volume" is a 1 km 'stand-off' radius. The coordinate frame for monitor and tasking volumes is the radial, in-track, cross-track (RIC) coordinate frame.

Each time data is received from the OSA, the CA Team is responsible for processing the data and providing risk assessment analysis results to the mission stakeholders. The close approach prediction information is processed and the collision risk is assessed probabilistically. The GSFC CA Team has

developed and implemented a set of tools called the Collision Assessment System (CAS) which is used to generate reports and perform event evaluation. (Further details concerning the architecture and operation of the CAS may be found in References 2 and 3.) The automated software is used to analyze each OCM that was received and create an analysis package called the OCM Analysis Report. The CA Team analyzes each OCM Analysis Report as well as accompanying data regarding the orbit determination quality for the secondary object to identify which close approach events pose a potential threat. For objects considered to be a threat, the CA Team works with the member missions to plan any necessary risk-mitigating actions. This process is discussed in detail in Reference 2. Risk mitigation maneuvers executed by the spacecraft mission teams using this process from January 2005 through the present are listed in Table 2.

Table 1: Safety Volume Definitions

	LEO Safety Volumes			GEO Safety Volumes
	Radial (km)	In-Track (km)	Cross-Track (km)	Stand-off Radius (km)
Monitor Volume (ellipsoid)	±2	±25	±25	40
Tasking Volume (box)	±0.5	±5	±5	15
Watch Volume (sphere)	1 km stand-off radius			2

Table 2: Maneuvers Performed to Date

	Asset ID	Secondary ID	Secondary description	Maneuver Date	TCA (Z)
1	Terra	14222	SCOUT G-1	10/21/05	10/23/05 20:53:28.794
2	TDRS	21019	S/L-12 (R/B)	1/2/06	1/4/06 18:11:19
3	PARASOL	81257	Analyst Sat	1/16/07	1/17/07 08:43
4	SAC-C	14345	SL-8 DEB	2/16/07	2/18/07 14:28
5	Terra	31410	FengYun 1C DEB	6/22/07	6/23/07 21:44
6	CloudSat	28893	SINAH 1	7/4/07	7/6/07 06:51:11.775
7	Aura	1399	TRIAD 1 debris	6/26/08	6/27/2008 15:34
8	CloudSat	8542	Delta I deb	7/20/08	7/21/08 04:38:25.931
9	TDRS-5	18384	Cosmos 1888	10/1/08	10/4/2008 21:05
10	PARASOL	31293	FengYun 1C DEB	10/19/08	10/20/2008 10:59
11	TDRS-3	20836	SL-12 R/B (2)	1/27/09	1/30/2009 16:34
12	CloudSat	33767	Cosmos 2251	4/23/09	4/24/09 13:29:50

DEBRIS ENVIRONMENT CHARACTERIZATION

One of the key issues to estimate projected conjunction assessment effects on operations for any spacecraft mission is to determine the predicted collision risk over the entire lifetime of the mission. In order to estimate how many high interest events a mission will see over its lifetime, the NASA Robotic CA Team performs debris environment characterization analysis. This helps the mission to plan an operations concept for supporting High Interest Events and to budget for the support required. Several methods have been used by the CA Team to predict the mission risk. One of the analysis techniques used has been to use

the close approach statistics collected over the past five years to characterize the various orbit regimes through analysis. However, because the highest risk events are relatively rare, there was concern that using the operationally collected statistics may not be a large enough sample to get a true estimate of the expected risk. Therefore, additional analysis [Ref 5] was performed to examine the probable frequency of future close approaches using Extreme Value Theory (EVT). EVT is a rigorous framework for estimating the occurrence of rare events and provides techniques for predicting the frequency of close approaches even when close approaches have not been observed historically. Based on the observed minimum miss distance statistics to date, the probability of exceeding any given minimum miss can be determined. The following paragraphs detail each method used to perform debris environment characterization and describe the risk assessment information obtained.

Proxy Spacecraft Screening (prediction)

To date, the most rigorous method for determining the expected debris flux for a given mission is through screening a proxy spacecraft. A proxy spacecraft is an operational spacecraft already in the orbit of interest which is monitored for conjunctions for some period of time. The proxy method provides actual conjunction data. Because very close approaches are somewhat rare, it may take a considerable amount of time to observe small miss distances using the proxy method. This method requires that a proxy spacecraft exists in the orbit of interest and that resources are available to provide screening of the proxy spacecraft. This method is also the most accurate method to determine the true operational impacts in a given orbit regime, and is most useful when a large set of data already exists for that orbit regime. For example, the considerable experience on the Earth Observing System (EOS) missions Aqua, Aura, and Terra have been used to provide regime characterization for upcoming missions planning to fly in similar orbits such as the Orbiting Carbon Observatory (OCO) and Glory.

Two Line Element (TLE) Simulation and Flux Ratios (prediction)

A quicker method for determining the debris flux for a given orbit is through direct simulation of the publically available (TLE) catalog. This method propagates both the full space object catalog and the reference orbit, counting the number of close approaches between catalogued objects and the reference orbit. The drawback to the direct simulation method is obvious in that it requires propagation of nearly 13,000 space objects over the period of time of interest, which may be years. However, since this method is really concerned with determining an average flux through the reference orbit, high fidelity, accurate propagation usually is not required. Analytical propagators accounting for the J2 perturbation and simple atmospheric density models suffice on the time-scales typically required. However, for long term studies, solar flux models accounting for the 11-year solar cycle should be considered.

This direct simulation method can, at best, determine a flux through a given orbit regime. However, the publically available catalog does not necessarily contain all space objects, and the methodology itself produces an average flux. A simple extension of this method is to compare the flux determined from this methodology with a similarly computed flux for a well known regime. For example, an extensive CA operational history (number of risk mitigation maneuvers performed, number of waived – off routine station-keeping maneuvers) is available from screening the EOS spacecraft for the last several years. By determining the ratio of a new orbital regime to that of the EOS regime from the TLE simulation method, an estimate of the actual operational impacts to the new mission can be determined. For example, an average EOS mission is known to have approximately 0.15 RMMs per year. If analysis determines that a new orbit has twice the debris flux as the EOS regime, 2x0.15 RMMs can be expected for the new mission.

The TLE analysis, while requiring significant computing time, is still quicker and potentially less expensive than the proxy methodology. However, the flux determined should be taken as an estimate of the true flux. Using this analysis and comparing it to a regime that is well known from operations provides a more robust estimate of the operational impacts. The next section discusses the statistics that have been collected for the EOS regime and used in these types of analyses.

Statistics (observation)

Several methods for predicting debris flux and high interest conjunction events have been presented. These have been based on analogous systems, indirect or proxy observations, or direct simulations and analysis. It is important to validate these models using historical data.

As previously mentioned, the NASA Robotic Conjunction Assessment Team has had a CA operations concept in place for over four years for many different asset missions. Most notable are the Earth Observing System (EOS) missions, Aqua, Aura, and Terra. These missions operate in sun-synchronous, 705 km mean equatorial height orbits. Performing real-time routine CA operations for these missions not only allows for in situ conjunction risk assessment and analysis, but it also provides a large amount of operational historical data on which to validate the other methods for flux and event predictions. Figure 1 shows the number of unique Monitor Volume conjunctions per month for the Aqua, Aura, and Terra missions. Though there are many short-periodic oscillations in the number of conjunction events, the long-term trend is fairly stable with a slightly increasing linear slope, with the exception of a few distinct disconnects. These discontinuities are attributable to large-scale changes in the local debris environment. Moreover, Figure 1 specifically calls out two of these largest environment-changing events: the Chinese ASAT Test in January 2007 and the Iridium 33/Cosmos 2251 collision in February 2009. These two events generated a significant amount of debris in the EOS regime, increasing the observed debris flux almost instantaneously.

Figure 2 presents similar data to that of Figure 1 for the Tracking Data and Relay Satellite System, a group of nine GEO satellites. The Monitor Volume used for GEO satellites is larger than that used for the ESC as it is a 40 kilometer sphere around the asset spacecraft. It is observed that the number of conjunctions at GEO is much less than that observed in LEO and is much more random over time.

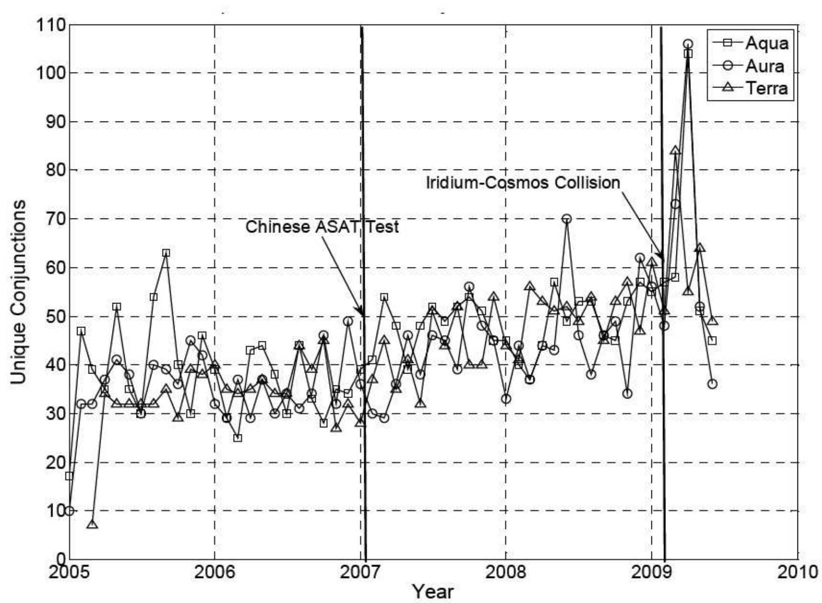

Figure 1: Unique Monitor Volume Conjunctions per Month for Aqua, Aura, and Terra

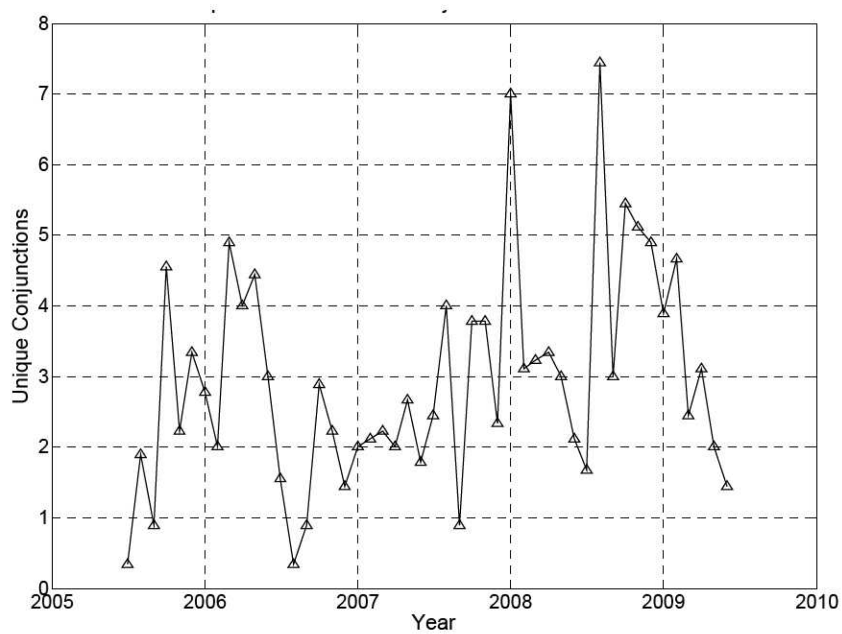

Figure 2: Unique Monitor Volume Conjunctions per Month for the TDRSS

In addition to the conjunction flux observed, it is also important to compare the prediction of high interest, or more rare, events. These comparisons will help demonstrate, and validate, the statistical and analytical models discussed previously. Figure 3 presents the minimum miss distance observed per month of routine CA operations. Similarly, Figure 4 presents the maximum Probability of Collision, Pc, observed per month. Both Figure 3 and Figure 4 represent statistics for all spacecraft for which the routine CA is currently being performed, including EOS and TDRSS. These figures help to provide a historical picture of the rare events; in this case, the minimum miss distance and maximum Pc observed. Based on these observed data points alone, many small miss distance and high probability events have occurred. These statistics indicate that the "big sky" philosophy is no longer realistic and justify the need to perform routine conjunction assessment.

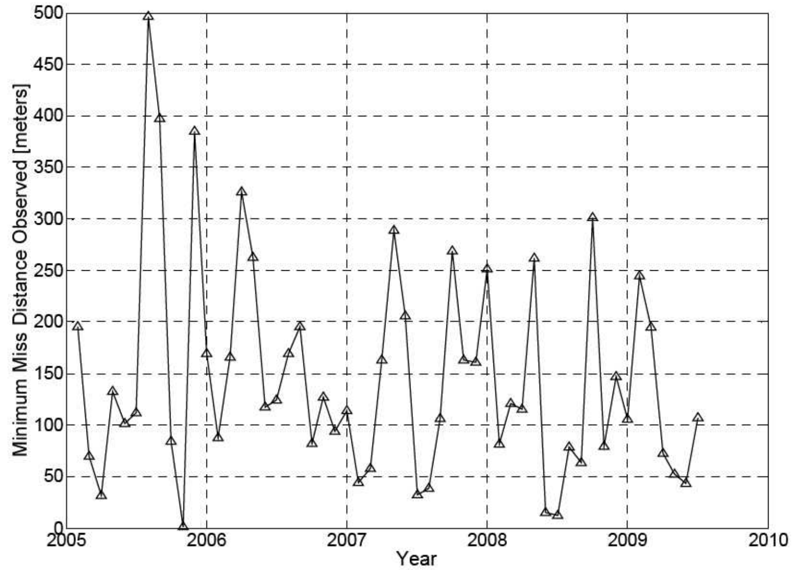

Figure 3: Minimum Miss Distance Observed Per Month

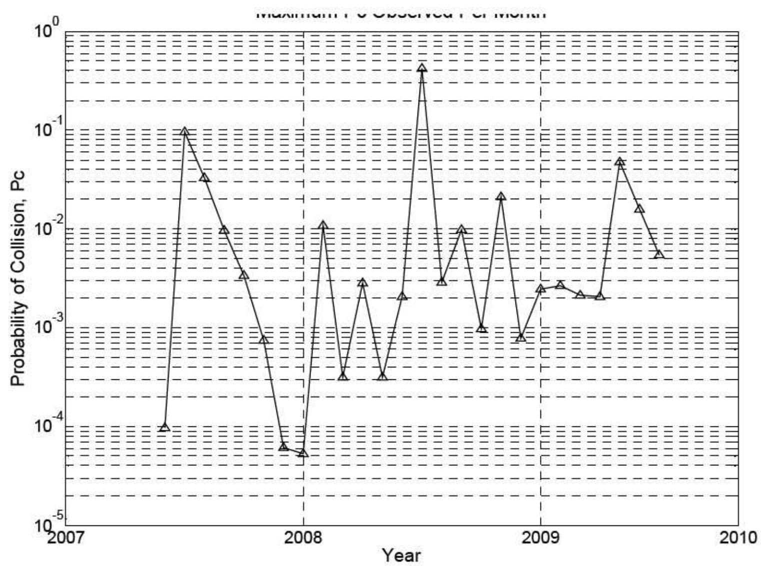

Figure 4: Maximum Pc Observed Per Month

Extreme Value Theory (EVT) (forecasting)

The TLE method requires significant computing time. The proxy method suffers from attempting to characterize the probability of future events based on past statistics, which offers no insight into the probability of rare events that have not been observed. This shortcoming may be overcome by use of EVT. As the name implies, EVT is concerned with the estimation of extreme, or rare, events. EVT attempts to determine the statistical structure of extreme random events, or, in other words, the tails of the distributions describing the random events, even when these extreme events have not been directly observed. When sampling a population of suitably random events, it is typically easy to fit a distribution curve to the bulk of the observed data. However, rare events which define the tails of the distribution are by definition sparsely observed. The sparseness of the data makes it difficult to precisely fit the tails of the distribution.

Assessing the probability of events outside of what has been observed based on poorly-fitted tail distributions is problematic at best.

A full analysis of using EVT for conjunction risk prediction is documented in Reference 5; however, an example is excerpted from that reference herein. This paper uses, as an example, historical miss distance statistics from the Aqua spacecraft to characterize the statistical nature of extremely small conjunction miss distances in the sun-synchronous, 705 km orbit regime. The background for EVT is documented in Reference 6 and its associated references. The basics of EVT will not be presented here. However, in summary, given a set of independent random events $\mathbf{X} = (X_1, X_2, \ldots, X_n)$ observed over some data block (e.g. a period of time), let the maximum of each set be denoted as $M_n = \mathrm{Max}(X_1, X_2, \ldots, X_n)$. The distribution of M_n for multiple data blocks will tend toward an Extreme Value Distribution (EVD). Three specific forms of EVD are typically used. For the distribution of miss distances, the Weibull distribution was the most appropriate:

$$\textbf{Weibull (EV2):} \qquad G_{2,\alpha}(x) = \exp(-(-x)^{-\alpha}), \quad x \leq 0 \qquad \mathbf{1}$$

Where x is the random variable miss distance, and α is the distribution shape parameter.

A location and scaling parameters μ and σ can be included as well via the transformation:

$$x = \frac{x - \mu}{\sigma} \qquad \mathbf{2}$$

Equation 1 is actually a specific form of a single, more generalized distribution often referred to as the gamma parameterization of the EVD. It has been shown that under reasonable conditions, this distribution is a limiting distribution. Therefore, Equation 1 and the common gamma parameterization are the only viable extreme value distributions [Ref 6]. The previous discussion assumed that we were interested in the maximum observed in blocks of data. The analysis on conjunction miss distances presented later will be concerned with minimums. A minimum problem can be converted to a maximum problem simply by changing the sign of the data being considered.

One of the goals of EVT is to predict the occurrence of rare events that may exceed values that have been observed in the past. One tool used to do this is the T Level [Ref 6]. The T Level is the threshold u(T) such that the mean number of exceedances of u(T) over the time span T is 1. Our interest is in predicting T Levels for predicting the exceedances of minimum miss distance thresholds. The process of determining T Levels begins by recording the maximum of a desired metric over a period of time. For the analysis that follows, the minimum monthly miss distance will be recorded. The set of extremes (maxima or minima) are fit to the EV distribution given in Equation 1. Methods and tools for fitting data to this distribution are available in the literature and will not be repeated here [Ref 6]. Once the EV distribution function is known, the threshold is computed by

$$u(T) = G^{-1}(1 - 1/T) \qquad \mathbf{3}$$

Where T is the number of time units. The unit of time is determined by the original grouping of the data. If the extrema were recorded per month, then T is in months; if the data was recorded per year, then T is in years, etc. Also, the probability that an event in any given time unit will exceed the threshold is given by

$$P\{X > u(T)\} = 1 - G(u(T)) = \frac{1}{T} \qquad \mathbf{4}$$

Once the distribution function, G, is known, Equation 4 gives insight into the probability of extreme events occurring even if those events have not been observed. This is a powerful risk assessment tool that provides rigor to the estimation of rare, yet risky events based on past experience. These techniques can be applied to the miss distances observed on the Aqua spacecraft over the previous three years.

The monthly minimum miss distances observed between the Aqua spacecraft and other space objects was chosen as a test case. Ref 5 has the full results, but only the Aqua results are shown here as a representative case (Figure 5). Forty months of data spanning May 2005 through August 2008 were analyzed. It should be noted that this data was taken directly from the GSFC CA Database and no effort was made to validate the minimums recorded. Some of the reported minimums may be a result of poor orbit determination solutions and may therefore not be valid. Further, rigorous studies should verify the validity and uniqueness of the data sets.

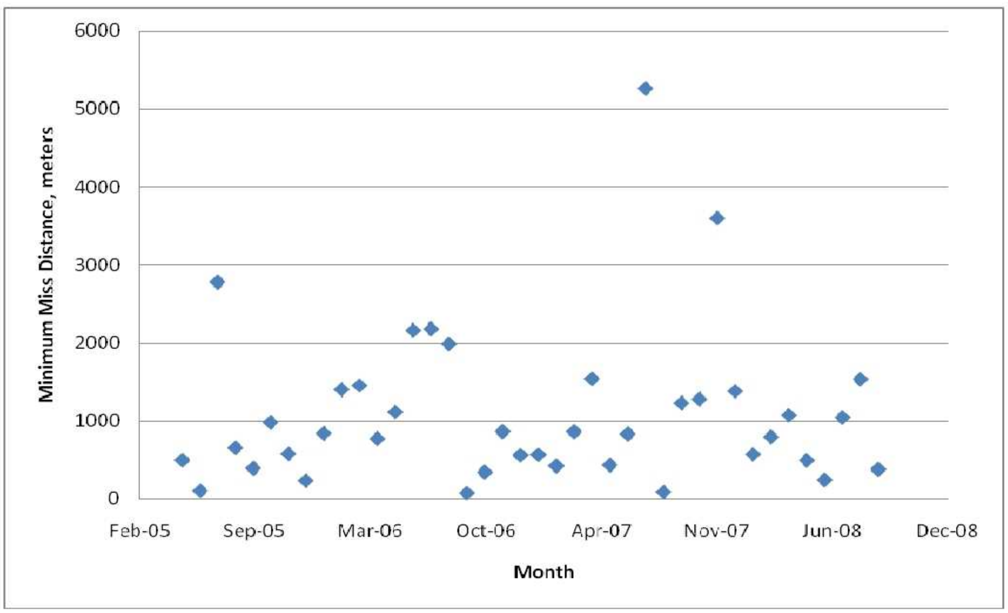

Figure 5. Aqua Monthly Minimum Miss Distances in Meters. May 2005 – August 2008.

The data were determined to fit the Weibull (EV2) distribution quite well:

$$G_{2,Aqua}(x) = \exp(-(-\frac{x}{1178.320})^{-1.22433}), \quad x \le 0 \qquad \mathbf{5}$$

In Equation 5, both the α value from Equation 1 and the scale parameters, σ, from Equation 2 have been estimated using least squares techniques to provide the best possible fit. Now that the distribution function has been determined, Equation 4 can be used to produce two plots for each group of data. First, the probability of exceeding a given miss distance in any one month is plotted in Figure 6. Second, the

number of expected months before exceeding a minimum miss is plotted in Figure 7. As an example, the statistics for both 20 m and 10 m miss distances are summarized in Table 3.

Table 3. Statistics for Aqua

Probability of 20 m Miss in any Given Month	0.68%	**Expected Number of Months to Observe 20 m Miss**	147
Probability of 10 m Miss in any Given Month	0.29%	**Expected Number of Months to Observe 10 m Miss**	344

The data shows that there is less than a 2% chance of seeing a 20 meter miss distance in any given month. The utility of this methodology lays less in verifying statistics for Aqua, but in how it may be used to characterize the debris threat for new missions. Whether a simulation approach is used or data is collected on a proxy spacecraft, EVT allows the time period over which data is collected to be shortened because EVT can extrapolate the probability of small miss distances without having to wait for those small distances to occur (either in simulation or real-time).

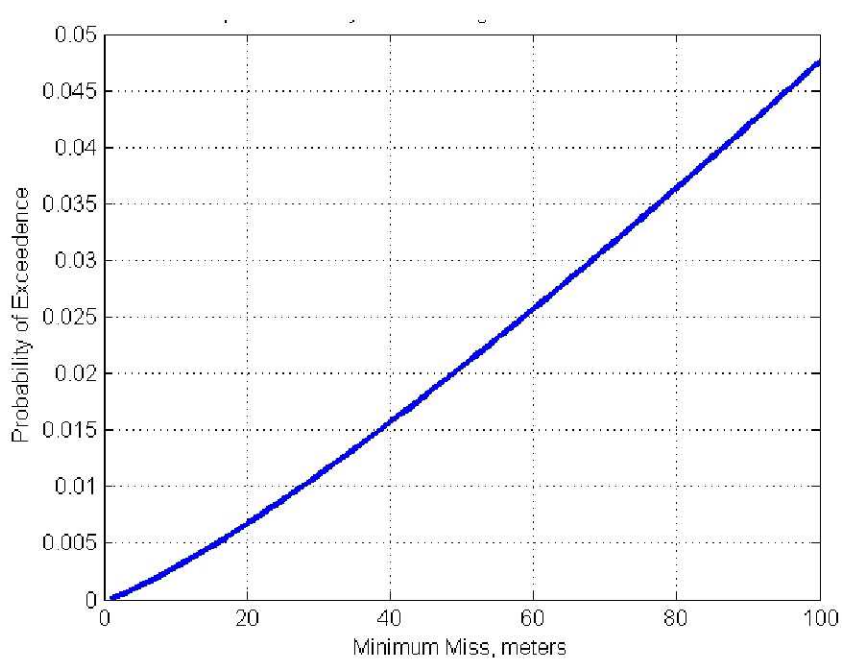

Figure 6: Aqua Probability of Exceeding Minimum Miss Distance in a Month.

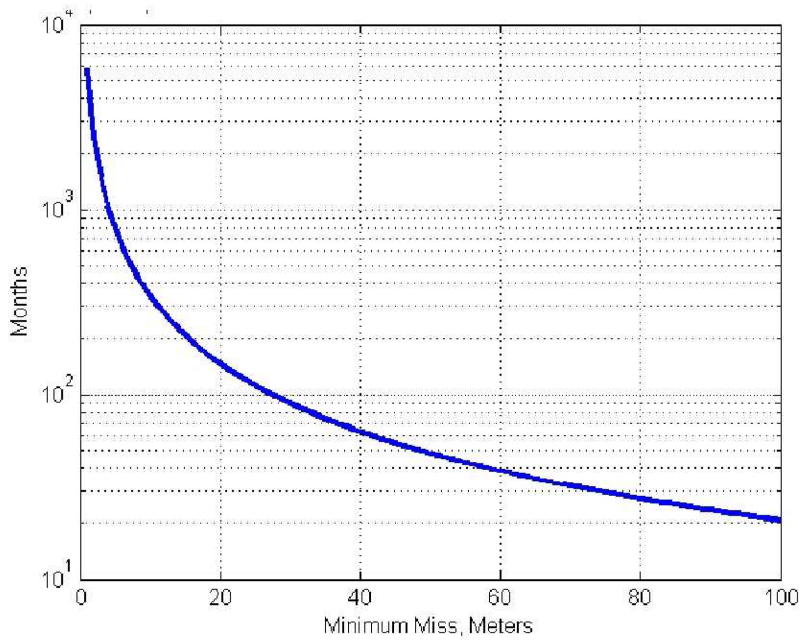

Figure 7: Aqua Expected Number of Months to Exceed Minimum Miss.

The results of the study in Reference 5 show that EVT is a mathematically rigorous tool for predicting the statistics of rare events based on past observations. The EV distribution functions and the concept of the T Level have been shown to predict the probability of rare events even when those rare events have never been observed. Results for the Aqua example show that the probability of observing a 20 m miss distance in any given month is less than 2%. The expected number of months it is predicted to take to observe a close approach with an extremely small miss distance is quantifiable and is shown to be on the order of the duration of a typical mission. This fact further invalidates the "big sky" concept that the risk of collision is too small to worry about. The threats due to close conjunctions are of high enough probability of occurrence to warrant implementation of a robust conjunction assessment operations concept. It should be noted that miss distance is not the only metric that could be used in this analysis. It is well known that miss distance alone does not quantify the risk associated with a given conjunction. The probability of collision metric could also be used, and may actually be a more appropriate metric to quantify collision risk. However, greater care must be taken to ensure that the maximal probabilities used in any such analysis are valid and based on good orbit determination solutions.

IRIDIUM 33 / COSMOS 2251 COLLISION EVENT SUMMARY

The *Iridium 33/ Cosmos 2251* collision occurred at an altitude of 788.6 km at 72.5 degrees North Latitude and 97.9 degrees East Longitude (over Siberia), with a relative approach angle of 102.5 degrees. The relative approach angle, which is the angle between the velocity vectors of the two objects, shows that this event was essentially a 'crossing' approach. Table 5 lists mean orbit elements for both satellites. The collision between an Iridium communications satellite and another object was identified by the sensors of the Space Surveillance Network (SSN) and the Joint Space Operations Center (JSpOC) on Tuesday, 10 February after the collision had occurred when a support request was received from Iridium. There are currently about 1000 debris objects associated with this event. During post-event analysis utilizing the observations obtained just prior to the time of closest approach (TCA) of 10 February 16:55 Z, the predicted miss distance computed was 223 m and the estimated conjunction probability was zero. However, it was later learned that the Iridium 33 satellite performed two small maneuvers several hours

prior to the collision as part of its planned, routine constellation maintenance. However, Iridium was not aware of the possibility of a collision because there was no established conjunction assessment process in place and therefore Iridium received no advance information to indicate a concern. After the collision, the Owner/Operator (O/O) ephemeris including the planned maneuver was analyzed and yielded a predicted miss distance of 60 m. This situation exemplifies the importance of having a routine Conjunction Assessment process in place for missions flying in the dense LEO regime, and that the process must include coordination that allows for screening of planned maneuvers. The remaining sections of this paper address the Iridium/Cosmos collision in detail, as adapted from Reference 7. Distribution properties of the current and future debris set are presented and an estimate of the increased collision risk to the ESC is discussed.

Table 4: Orbital Elements at TCA

	Apogee Height (km)	Perigee Height (km)	Inclination (deg)
IRIDIUM 33	772	762	86.4
Cosmos 2251	804	788	74.0

The following figures show the evolution of the event based on the post-event analysis results provided by the JSpOC. The values presented in the trends are computed at the closest approach point. Included is the total miss distance, the relative miss distance components expressed in the radial, in-track, cross-track (RIC) reference frame, and the conjunction probability. Although the collision event was not actively monitored prior to the time of closest approach, observations of both objects were available. The event trends that follow use both predictions that go back seven days prior to the TCA as well as calculations that were generated after the TCA to establish a full historical picture of this event.

Figure 8 shows the miss distance evolution at the close approach point on Tuesday the 10th of February. The first solution, based on data collected seven days prior to the TCA, gives a predicted miss distance of 302 m. The minimum miss distance prediction was 60 m, resulting from the O/O ephemeris that reflected the planned maneuver. This ephemeris was provided to the JSpOC by Iridium after the event took place.

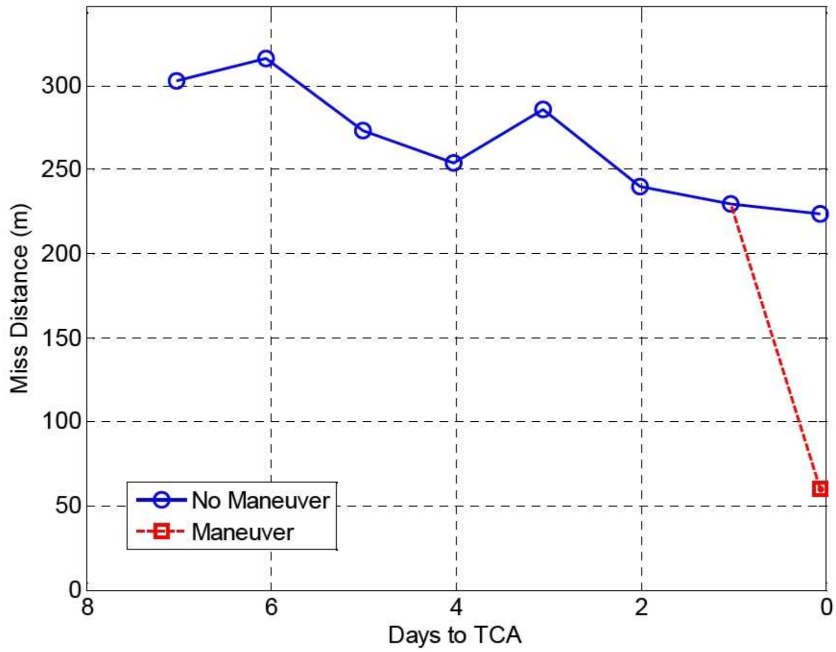

Figure 8: Miss Distance Evolution

Little change in the relative miss distance components was observed throughout the 7-day time span (Figure 9), but the largest changes were observed in the uncertainties of the relative in-track and relative cross-track components. These orbital uncertainties get smaller for shorter prediction times.

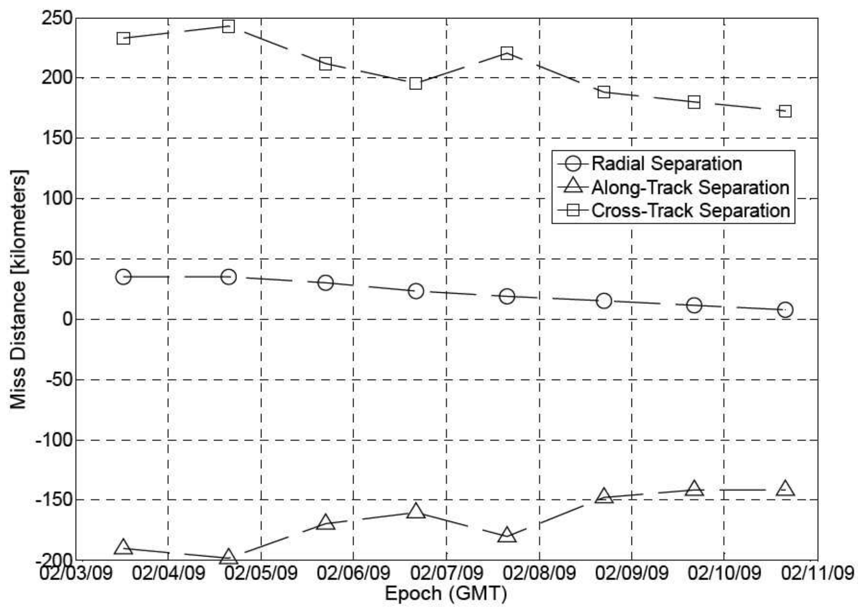

Figure 9: Miss Distance Component Evolution

The conjunction probability (P_c) between two objects is the probability that the two objects' centers of mass will come within a specified distance of each other. This calculation takes as inputs state vector and

state vector uncertainty information as well as the miss distance "keep-out" region. For this event analysis, a 20 meter keep-out region was used in each of the probability calculations.

Figure 10 shows the P_c evolution for each of the post-event generated close approach solutions based on JSpOC-generated data. The blue circles show the P_c trend based on the JSpOC solutions which do not include the Iridium maneuver. The first four P_c values were consistently on the order of 1e-3. As the orbit uncertainties decreased, particularly in the in-track direction, the P_c dropped several orders of magnitude to 4.5e-8, and then eventually became zero at the TCA – 2 day point. The red squares depict the P_c using ephemeris that reflected the Iridium maneuver along with a representative covariance. A P_c value of 4.98e-3 was obtained that more accurately reflects the threat level of the event at TCA. Again, this data was obtained after the collision.

Throughout the close approach predictions, the miss distance was slowly decreasing, though there was little change from solution to solution observed. Moreover, the uncertainty in position of the two objects was also decreasing at a much faster rate. At the TCA - 2 day prediction, the combined uncertainty of two objects decreased below that of the miss distance and, hence, the conjunction probability had dropped to zero. At this point, the CA Team would have concluded that the conjunction was not a risk. However, as previously mentioned, the Iridium-33 satellite performed a maneuver prior to TCA, essentially maneuvering into the Cosmos payload. As part of the NASA Robotic CA procedure, owner/operator ephemerides which model any planned maneuvers are routinely screened in addition to the JSpOC solutions. This additional data is reflected in Figures 8 and 10, which show that the miss distance was 60 meters and the P_c was 4.98e-3. This information would have prompted the CA Team to recommend that the planned Iridium maneuver be waived off.

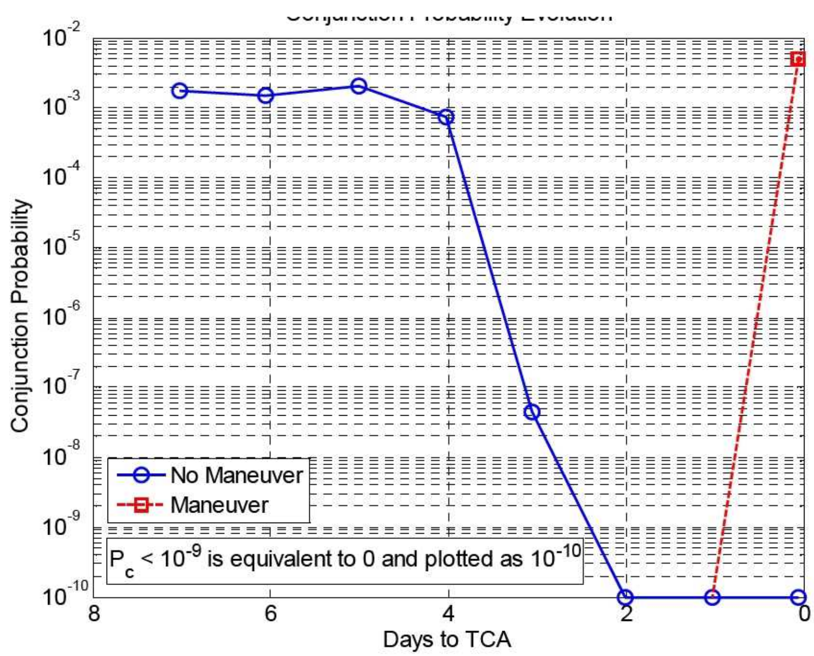

Figure 10: Conjunction Probability at TCA

Shortly after the collision between Iridium 33 and Cosmos 2251, the Joint Space Operations Center (JSpOC) began cataloging debris objects from the observations provided by the Space Surveillance Network (SSN). Approximately 20 pieces were cataloged on the 18th of February, and there have been

approximately 730 (226 Iridium and 504 Cosmos) pieces of debris cataloged to date. Figure 11 displays the number of objects that have been cataloged per day as of March 20, 2009.

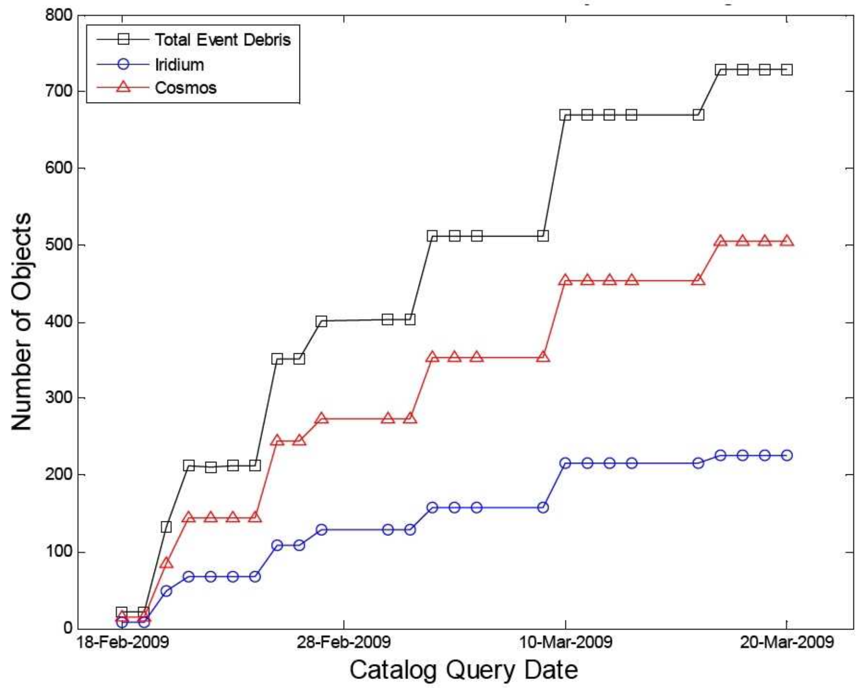

Figure 11: Debris Objects Cataloged Per Day

Figures 12 through 14 provide the distribution of various orbital parameters for the debris pieces that have been cataloged for both Iridium 33 and Cosmos 2251. These plots and statistics were generated using the Iridium and Cosmos debris states. These debris states were based on Two-Line Element (TLE) set data obtained from the Space Track website on March 20, 2009.

Figure 12 displays the mean equatorial height distribution of the combined Iridium 33 and Cosmos 2251 debris. The mean is 778 km, which is approximately the height at which the collision event occurred (788.6 km). The minimum height value is 284 km and the maximum height value is 876 km. Also shown in Figure 12 is the position of the Earth Science Constellation (ESC) with respect to the debris height distribution. The ESC altitude is denoted by the red dot. Examination of Figure 12 shows that 97 percent of the combined Iridium 33 and Cosmos 2251 debris lies above the current ESC operational equatorial altitude of 705 km.

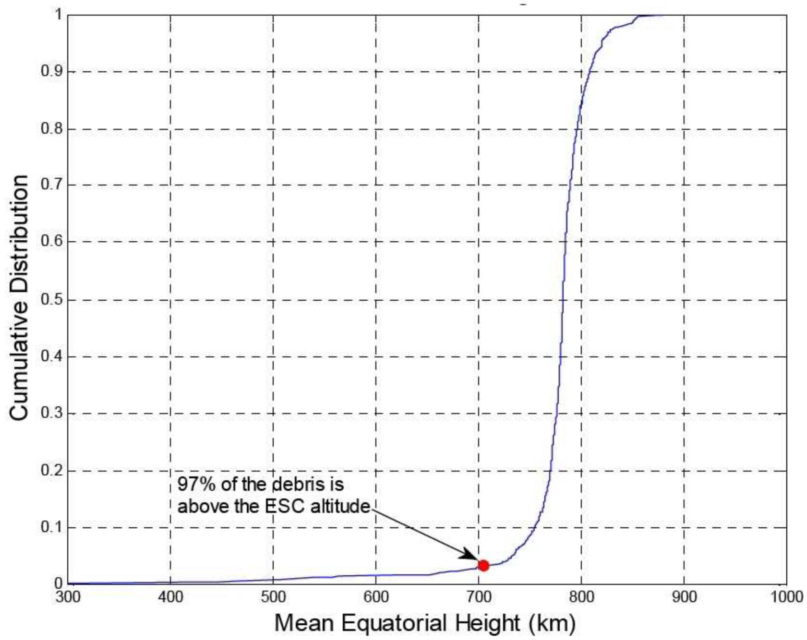

Figure 12: Combined Iridium 33 and Cosmos 2251 Debris Height Distribution

Figure 13 displays the mean equatorial height versus inclination for the Cosmos 2251 debris. The dispersion on the inclination range for the Cosmos 2251 debris is from 73.7 to 74.3 degrees. Figure 14 displays the mean equatorial height versus inclination for the Iridium 33 debris. The dispersion on the inclination range for the Iridium 33 debris is from 85.6 to 86.8 degrees.

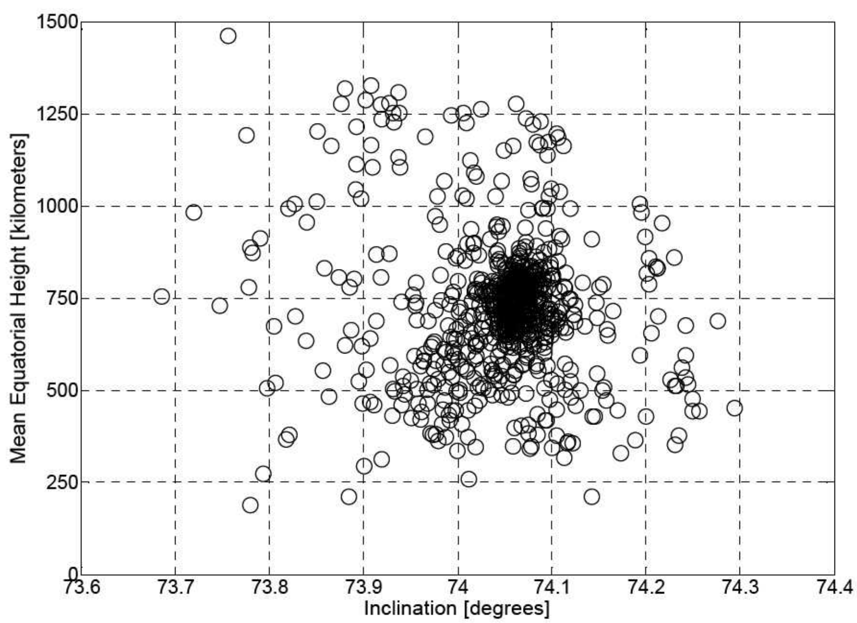

Figure 13: Cosmos 2251 Debris Distribution

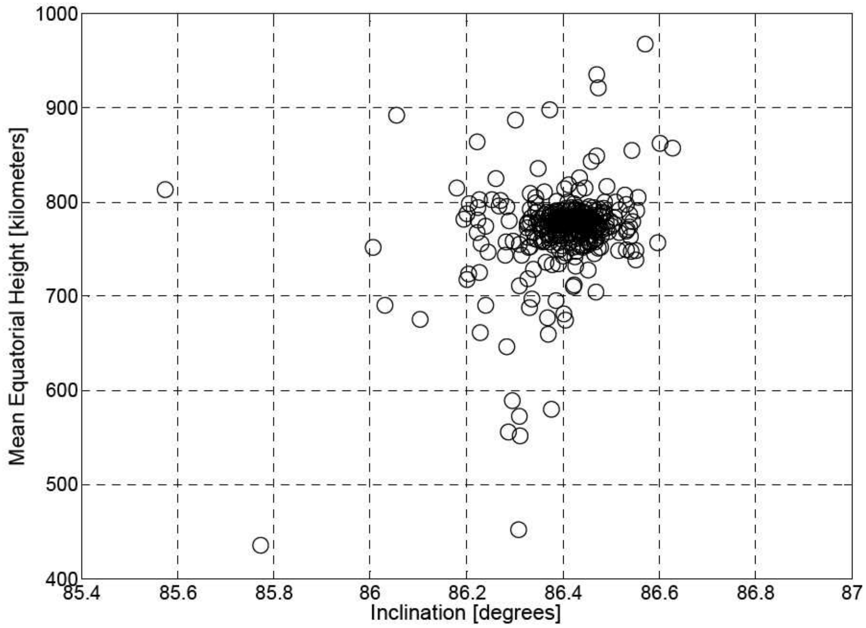

Figure 14: Iridium 33 Debris Distribution

LONG TERM EVOLUTION OF THE IRIDIUM/COSMOS DEBRIS

Several statistical distributions of the Iridium and Cosmos debris have been presented, which help to characterize the current state of the debris clouds. It is also important to examine the immediate effects on the Earth Science Constellation and local debris environment as well as the long-term effects of this debris as it evolves. This section estimates the current debris environment density increase and decay rate prediction for the centroids of the debris clouds.

Although the collision between Iridium 33 and Cosmos 2251 occurred roughly 80 kilometers above that of the ESC, the ESC has already observed 70 conjunctions with debris objects associated with that event as of 18 June 2009, across all member missions of the ESC. As an estimate, the debris environment density change can be calculated by examining the apogee and perigee height distribution. Counting the number of Iridium and Cosmos debris objects with apogee or perigee heights within 50 km of ESC results in approximately a 12-15% increase in the current debris environment for the orbital regime of ESC. This debris density was calculated using Two Line Element sets, comparing the apogee and perigee height distributions of objects near the ESC with and without the debris objects resulting from this collision. Table 5 provides the percentage of objects each debris cloud near the ESC as well as the percentage each cloud comprises the total debris objects around the ESC.

Table 5: Local Debris Environment Change Statistics

	Total Number of Objects	Number of Objects Near ESC	Percent of Objects Near ESC	Percent of Total Near ESC
Iridium 33 Debris	335	82	24.48	4.39
Cosmos 2251 Debris	786	230	29.26	13.38
All Space Objects	14,610	1,949	13.34	---

Since the collision, the ESC has already observed several conjunctions with debris objects associated with the collision. Table 6 presents the number of safety volume violations observed between the Iridium and Cosmos debris and the ESC.

Table 6: Observed Conjunctions

Mission	Monitor Volume			Tasking Volume			Watch Volume			Minimum Miss
	Iridium	Cosmos	Total	Iridium	Cosmos	Total	Iridium	Cosmos	Total	[meters]
Landsat-5 (14780)	19	63	82	0	4	4	0	1	1	90
Landsat-7 (25682)	20	39	59	0	4	4	0	0	0	1,179
Terra (25994)	12	48	60	0	4	4	0	1	1	408
EO-1 (26619)	11	36	47	1	4	5	0	1	1	620
SAC-C (26620)	10	57	67	1	3	4	0	2	2	850
Aqua (27424)	4	68	72	0	6	6	0	0	0	1,257
ICESat (27642)	7	14	21	0	1	1	0	0	0	1,546
Aura (28376)	6	67	73	1	9	10	1	4	5	341
PARASOL (28498)	6	46	52	0	2	2	1	1	2	889
CloudSat (29107)	9	64	73	1	4	5	0	2	2	52
CALIPSO (29108)	13	57	70	2	5	7	0	0	0	1,009
ESC TOTAL	**117**	**559**	**676**	**6**	**46**	**52**	**2**	**12**	**14**	**52**

An estimate of the decay rate of the entire debris cloud can be performed by examining the decay rate of a "mean" object at the centroid of each of the debris clouds. A debris object having the mean states as described by the previous statistical distributions was propagated over a long period of time. The initial mean states of the Iridium and Cosmos centroids are given in Table 7. For all propagations, modeling included an 8x8 geopotential model, Jacchia-Roberts atmospheric density, third body perturbations, and a RK8(9) integration method. For each centroid, a mean ballistic coefficient was applied. The Jacchia-Roberts atmospheric density models used the Schatten mean and plus 2 sigma nominal peak timing cycle solar flux predictions.

Table 7: Brower-Lydane Mean Elements of Iridium and Cosmos Debris Cloud Centroids

	Iridium Centroid	**Cosmos Centroid**
Semi-Major Axis [kilometers]	7167.7	7120.3
Eccentricity	0.0064	0.0145
Inclination [degrees]	86.4178	73.9834
RAAN [degrees]	106.9175	314.2651
Argument of Perigee [degrees]	227.2637	137.3130
Mean Anomaly [degrees]	131.169	223.2085
Coefficient of Drag	0.148783	0.148783

It was observed that the Cosmos centroid decayed to a mean equatorial height of 705 kilometers roughly around 2019 using the nominal Schatten solar flux predictions and around 2013 using the +2 sigma predictions. These decay predictions are shown in Figure 15. The Iridium centroid decayed to the ESC mean equatorial height in roughly 2044 using the nominal Schatten solar flux predictions and 2025 using the +2 sigma predictions. These decay predictions are shown in Figure 16. From Figure 15 and Figure 16, it is observed that Iridium debris will remain in orbit and, more importantly, above the ESC for much longer than the Cosmos debris. Although this estimation does not consider the steady increase in debris density over that time span, it does present the notion that the centroid of the debris clouds will remain above the ESC for many years and will slowly decay, steadily increasing the number of conjunctions resulting from this debris.

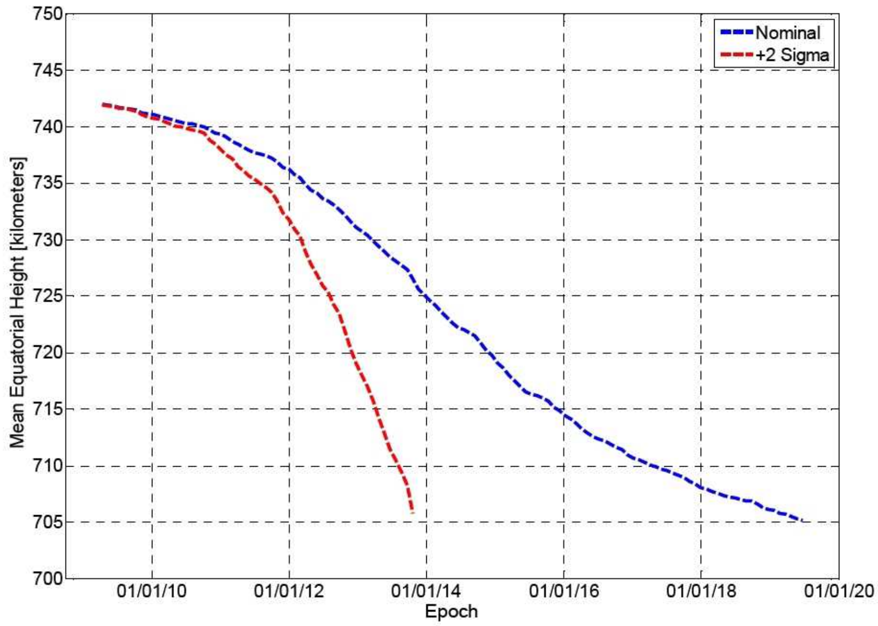

Figure 15: Cosmos Debris Centroid Evolution

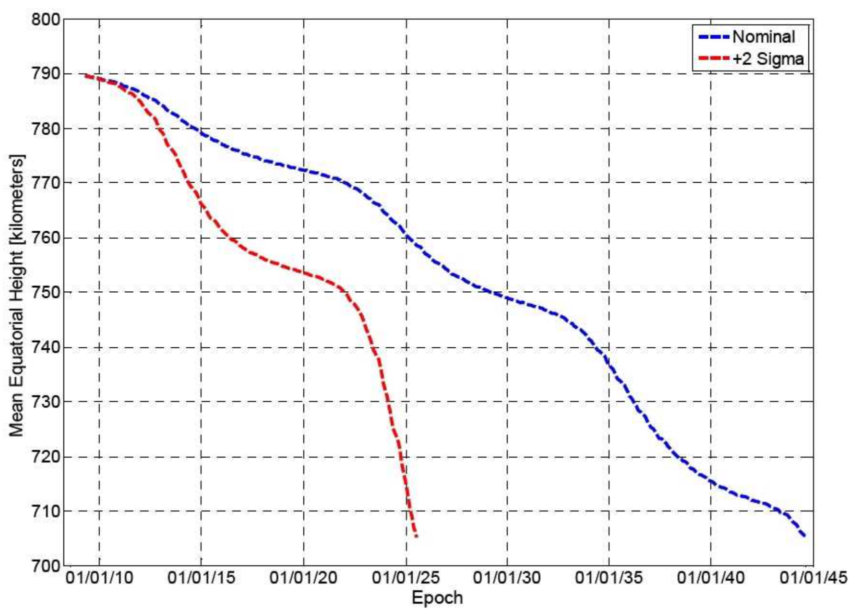

Figure 16: Iridium Debris Centroid Evolution

SUMMARY AND FUTURE WORK

This paper demonstrates through both operations statistics and analysis that the space environment is no longer sufficiently "big" to ignore the threat of collision from space objects, especially in the 700-800km orbit regime. The rapid growth in the debris environment and expected continuation of that growth requires diligent monitoring of close approaches as part of routine operations, especially for missions having the capability to execute a mitigation maneuver. Several methods were presented which allow the prediction of the number of close approaches to anticipate for missions in development. The impact of the

recent Iridium 33/ COSMOS 2251 collision on the NASA Earth Science Constellation was examined, and the operational statistics collected for the ESC missions were presented. The routine conjunction assessment process in use by NASA for its robotic missions has proven to be an effective tool for mitigation of risk due to close approaches, as indicated by the number of events mitigated since its inception in 2005. The experience base that has been built to evaluate the threats will continue to be broadened, as NASA seeks more efficient ways to evaluate the risk posed to its assets.

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